AN-1302
APPLICATION NOTE

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Optimizing the ADuCM350 for 4-Wire, Bio-Isolated Impedance Measurement Applications

INTRODUCTION

The ADuCM350 is an ultralow power, integrated mixed-signal metering solution that includes a microcontroller subsystem for processing, control, and connectivity. The processor subsystem is based on a low power ARM® Cortex™-M3 processor, a collection of digital peripherals, embedded SRAM and flash memory, and an analog subsystem which provides clocking, reset, and power management capability.

The ADuCM350 has the ability to perform a 2048 point single frequency discrete Fourier transform (DFT). It takes the 16-bit ADC output as input and outputs the real and imaginary parts of the complex impedance.

The configurable switch matrix on the ADuCM350 allows you to choose from a 2-wire, 3-wire, or 4-wire impedance measurement.

This application note details how to set up the ADuCM350 to optimally measure the impedance of an RC type sensor, using 4-wire techniques, while targeting IEC-60601 standards.

To target the IEC-60601 standard, the ADuCM350 is used in conjunction with an external instrumentation amplifier (AD8226), to complete high precision absolute measurements using a 4-wire measurement technique.

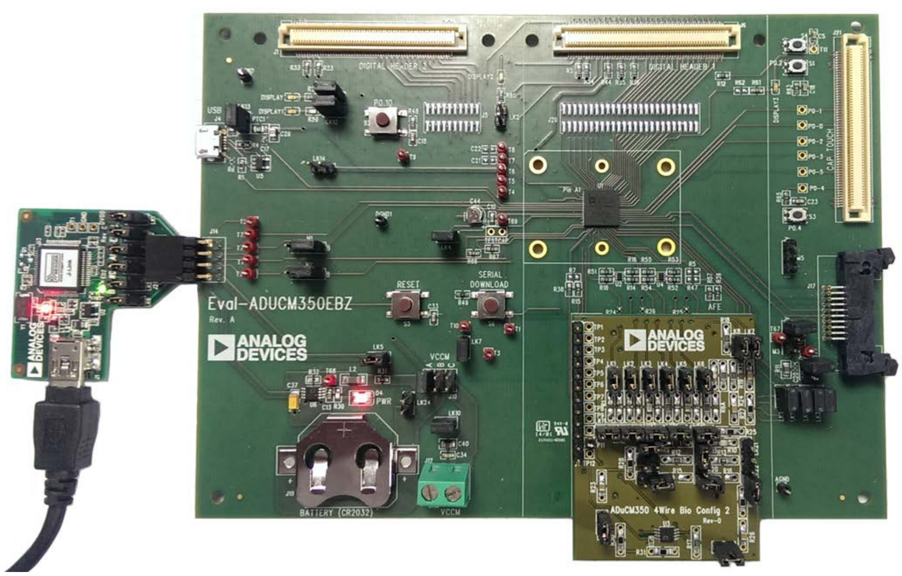

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Figure 1. EVAL-ADuCM350EBZ Motherboard and 4-Wire Bio-configuration Daughter Board

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REVISION HISTORY

4/14—Revision 0: Initial Version

CONFIGURATIONS

The ADuCM350 offers three configurations for measuring the impedance of a sensor.

2-WIRE SYSTEM

In the presence of varying access resistance to the unknown impedance, this configuration provides relative accuracy measurements for impedance magnitude and impedance phase. For further details on optimizing the ADuCM350 for 2-wire impedance measurements, refer to the AN-1271 Application Note, *Optimizing the ADuCM350 for Impedance Conversion*.

The 2-wire system measures the relative accuracy of Impedance magnitude and phase.

4-WIRE SYSTEM

This configuration provides absolute accuracy for both impedance magnitude and impedance phase measurements because access resistances are calibrated out. This configuration does not operate where ac coupling capacitors are required to isolate sensor from device, that is, capacitors in series with the access resistances. Refer to the AN-1271 Application Note, *Optimizing the ADuCM350 for Impedance Conversion*, for information on optimizing the ADuCM350 for 4-wire measurements.

The 4-wire system measures the absolute accuracy of impedance magnitude and phase, however isolation capacitors are not allowed.

4-WIRE BIO-ISOLATED SYSTEM

If isolation capacitors are required between sensor and device, then an external instrumentation amplifier is required to measure the differential voltage across the sensor. It is not possible for the ADuCM350 to do this measurement as a single chip solution because the isolation capacitors cause instability when included on the sense (P and N channel) paths.

The 4-wire bio-isolated system measures the absolute accuracy of impedance magnitude in the presence of isolation capacitors, however this system is not targeted for accurate phase measurements.

BASIC 4-WIRE IMPEDANCE MEASUREMENT

To measure the impedance of an unknown sensor, Z, a ratiometric measurement technique is employed using the ADuCM350.

1. Measure the impedance of a known precision resistor, RCAL, as shown in Figure 2. An excitation voltage is applied at RCAL 1 with associated D and P switches closed in the switch matrix. The resultant excitation current is measured through RCAL 2, with associated T and N switches closed in the switch matrix. This current is converted to a voltage using the TIA amplifier, where R_{TIA} is optimized for the maximum current seen by the ADC, and is converted to a voltage using the ADC. A 2048 point Hann sample is performed on the data to give real and imaginary components of the impedance.
2. Change the switch matrix configuration, as shown in Figure 3, and excite the sensor measuring the response current. The DFT engine now calculates the real and imaginary components of the unknown impedance, Z.
3. Calculate the unknown impedance magnitude on the core using the following equation:

$$ZUNKNOWN_{MAG} = \frac{ZUNK_{MAG}}{RCAL_{MAG}} \times RCAL$$

4. Calculate the unknown impedance phase on the core using the following equation:

$$ZUNKNOWN_{PHASE} = ZUNK_{PHASE} - RCAL_{PHASE}$$

This 4-wire measurement approach to measuring impedances operates if there are no isolation requirements on the sensor. However, if an isolation capacitor, such as C_{ISO}, need to be included in series with the access resistor, R_{ACCESS}, in a 4-wire measurement, then a single chip solution is not possible.

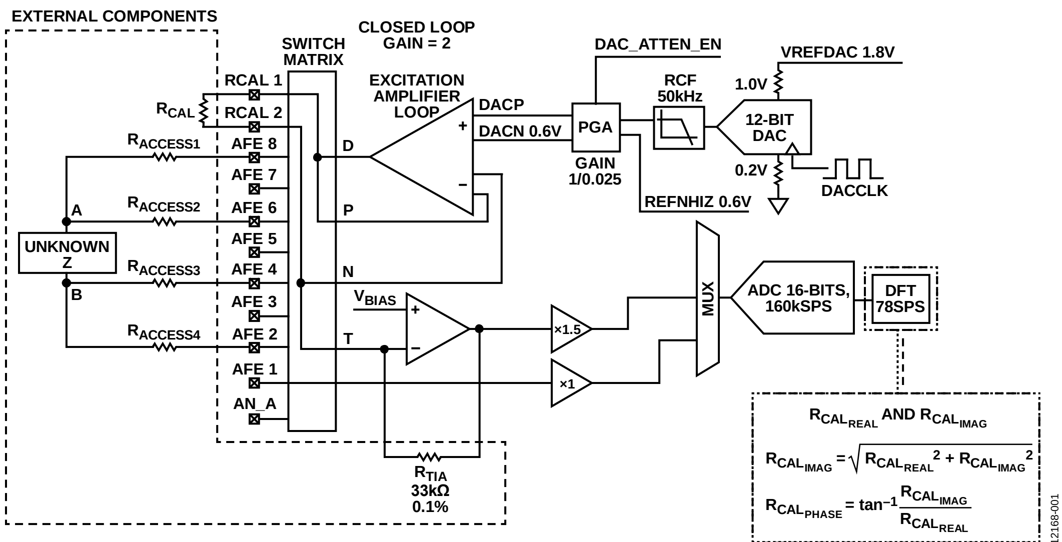
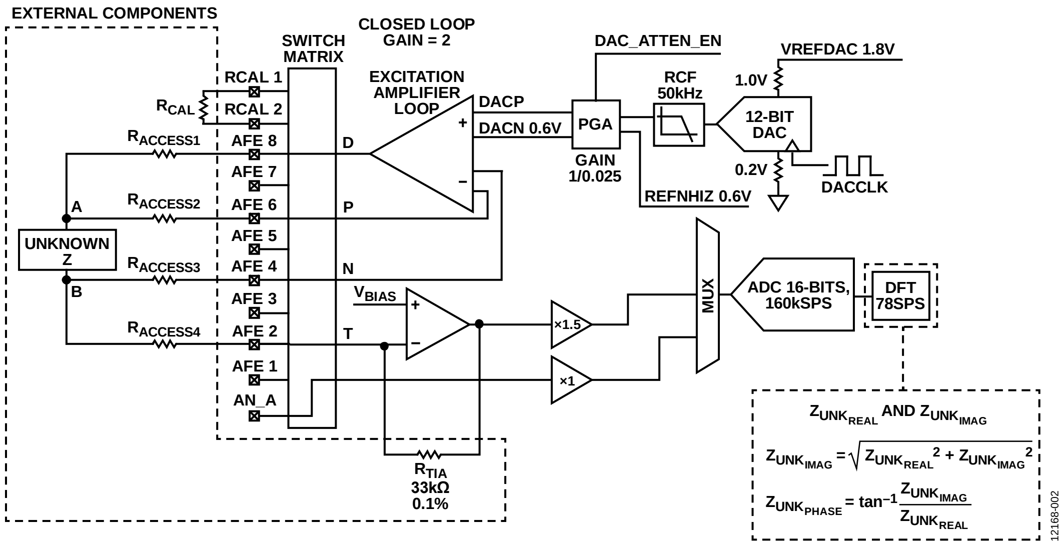


Figure 2. 4-Wire Topology for ADuCM350—Measuring RCAL



$Z_{UNK_{REAL}}$ AND $Z_{UNK_{IMAG}}$

$$Z_{UNK_{IMAG}} = \sqrt{Z_{UNK_{REAL}}^2 + Z_{UNK_{IMAG}}^2}$$

$$Z_{UNK_{PHASE}} = \tan^{-1}\frac{Z_{UNK_{IMAG}}}{Z_{UNK_{REAL}}}$$

Figure 3. 4-Wire Topology for ADuCM350—Measuring Z

THE 4-WIRE BIO-ISOLATED METHOD

BASIC 4-WIRE THEORY

In a classic 4-wire /4-terminal sensing system, a differential current source is used to force a known current into the sensor. This forced current generates a potential difference across the Unknown Z, which is to be measured according to Ohm's Law where:

$V = I \times R$

When the current is being forced, the access wires to Z also lead to a drop in voltage, which causes inaccuracies in a measurement. To remove this loss from the actual measurement of Z, a differential pair of sense lines are connected to Z at the points labeled A and B in Figure 2.

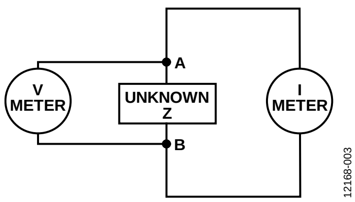


Figure 4. Basic 4-Wire Topology

The differential sense lines are designed with very high input impedance stages so that no current flows through them and there is no voltage drop across them. The impedance Z is then measured using the equation

$Z = V_{METER}/I_{AC}$

4-WIRE BIO-ISOLATED THEORY IN APPLICATION

An alternative approach is to use a high precision excitation voltage source as the force signal. Apply this voltage to Z and measure the response current using a high accuracy current meter (see Figure 3). The unknown impedance Z is then measured by the equation

$Z = V_{METER}/I_{METER}$

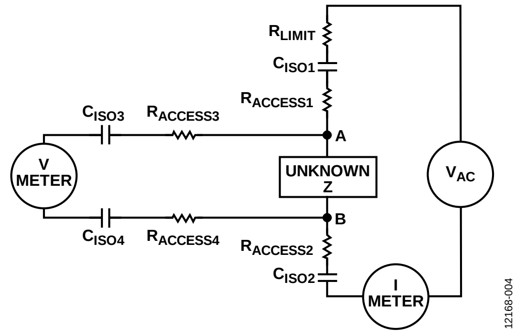


Figure 5. 4-Wire Bio-Isolated Topology

Referring back to Figure 3, it is possible to measure 4-wire impedance using the ADuCM350.The excitation stage excites the sensor with a known voltage, which is accurately differentially sensed using the internal instrumentation loop. The current response is measured through the TIA channel and converted to a voltage.

In a real-world application, such as those governed by the IEC-60601 standards, the Z (or sensor) allows a limited dc voltage across it. The restrictions on ac current forced on sensor are more relaxed. The ac voltage source is selected for the force connection to the sensor to utilize the ADuCM350 DFT capability.

In Figure 5, C_{ISO1} and C_{ISO2} are discrete isolation capacitors that ensure that no dc voltage appears across the sensor. $R_{ACCESS1}$ and $R_{ACCESS2}$ are access or lead resistance inherent in the connections to the sensor. R_{LIMIT} is an extra level of security to guarantee the maximum allowable excitation current seen by the sensor in a scenario where the R_{ACCESS} resistance is removed from the measurement.

A 4-WIRE BIO-ISOLATED SOLUTION

Referring to Figure 5, the following is required:

- Precision ac voltage source
- High precision current meter
- Precision differential voltage meter

Precision AC Voltage Source

The ADuCM350 has a high precision excitation control loop, which drives a precision ac voltage to the sensor. An internal differential sense configuration guarantees the accuracy of the voltage source (see Figure 6). The positive sense, P, is tied to the drive terminal, D, in the configurable switch matrix. A DDS based sine wave generator is used to generate the ac stimulus through a 12-bit DAC. For more information regarding the transmit stage, refer to the ADuCM350 Hardware Reference Manual (UG-587).

High Precision Current Meter

The ADuCM350 utilizes a TIA amplifier for current to voltage conversion for measurement by the high precision ADC, the gain of which is set by an external resistor, R_{TIA}. The TIA channel sinks the sensor excitation current and the channel is precisely biased on a common mode of 1.1 V. Significant analog and digital filtering is performed on measurement for rejection of interferers and noise. The T and N channels are tied together using the switch matrix for accurate sense capability on the current measured (see Figure 7).

The ADC converts the current measurement with a 160 kSPS ADC. A 2048 sample point DFT is performed on the data; resulting real and imaginary components for the current measurement are calculated.

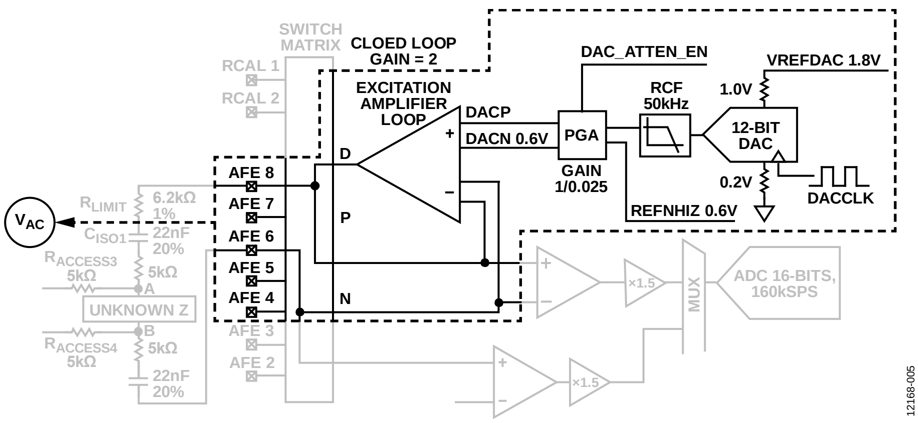


Figure 6. AC Voltage Source on the ADuCM350

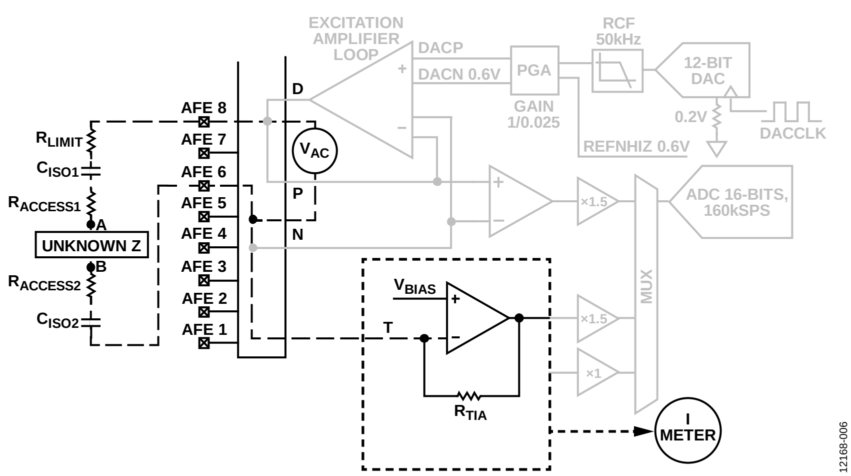


Figure 7. High Precision Current Meter

Precision Differential Voltage Meter

To differentially sense the voltage across the sensor, a low power instrumentation amplifier with excellent noise and common-mode rejection is required (see Figure 8). The AD8226 is selected for this application. It is referenced off the common mode of the system set by the V_{BIAS} voltage on the TIA channel. The output of the in-amp is fed back into the ADuCM350 through one of the auxiliary channels, for example, AN_A.

The ADC converts the auxiliary voltage measurement with a 160 kSPS ADC. A 2048 sample point DFT is performed on the data, and resulting real and imaginary components for the voltage measurement are calculated.

4-Wire, Bio-Isolated Measurement System Block Diagram

Figure 9 shows the combination of the following:

- Precision ac voltage source (ADuCM350 excitation stage)
- High precision current meter (ADuCM350 TIA channel stage)
- Precision differential voltage meter (AD8226 instrumentation amplifier)

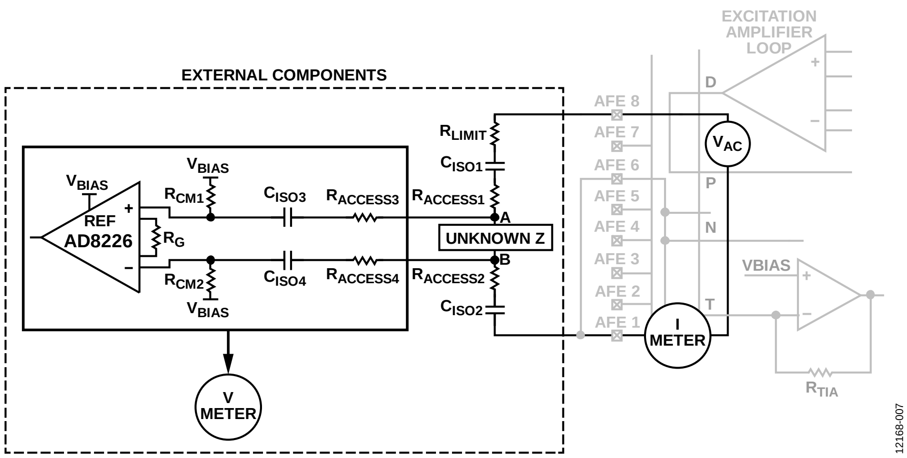


Figure 8. High Precision Differential Voltage Meter

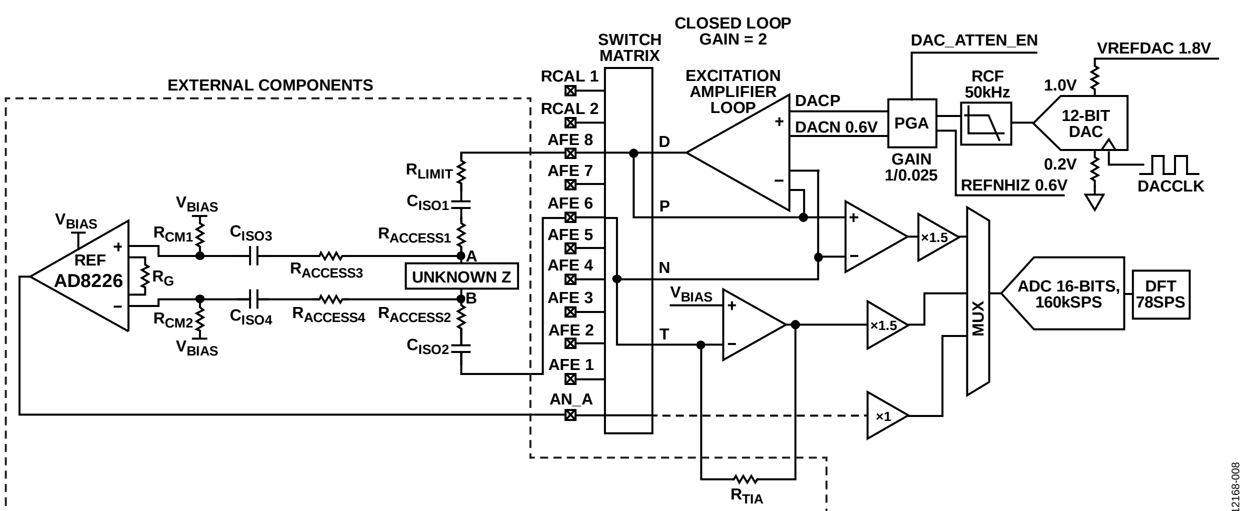


Figure 9. 4-Wire Measurement System using the ADuCM350 and the Instrumentation Amplifier (AD8226)

How to Calculate the Unknown Z

After obtaining the current and voltage DFT measurements, the part can exit the AFE Sequencer and calculate the impedance of the sensor using the following equations:

$$Voltage\ measurement\ magnitude = SQRT(r^2 + i^2)$$

$$Voltage\ measurement\ phase = ATan(i/r)$$

$$Current\ measurement\ magnitude = SQRT(r^2 + i^2)$$

$$Current\ measurement\ phase = ATan(i/r)$$

where *r* and *i* are the real and imaginary components from the voltage and current DFT measurements, respectively.

To calculate the Impedance Z, use Ohm's law by dividing the voltage magnitude by the current magnitude while taking into account the gains of the signal chain.

$$Z(Magnitude) = (Voltage\ magnitude/Current\ magnitude) \times (1.5/1.494) \times R_{TIA}$$

The current measurement value is converted to a voltage, using the R_{TIA}, for measurement purposes. This gain needs to be taken into account.

The 1.5 gain in the equation is the ratio between the gain of the ADuCM350 current measurement channel, which is 1.5, vs. the gain of the ADuCM350 voltage measurement channel which is 1.

The gain of the in-amp is determined by the selection of RG. For the AD8226, this is determined by

$$RG = (49.4\ \text{k}\Omega)/(G - 1)$$

Choosing

$$RG = 100\ \text{k}\Omega$$

results in a gain of 1.494.

Note that these equations are taken into account in the example provided in the software development kit.

EXAMPLE OF A 4-WIRE BIO-ISOLATED SYSTEM

SENSOR CONFIGURATION

In the example described in this application note, measure the impedance of an RC type sensor, with the configuration shown in Figure 10, for a 30 kHz excitation signal. Note that T_{OL} indicates tolerance.

The sensor details are as follows:

- C_S = 220 pF
- R_S = 20 kΩ
- R_P = 100 kΩ

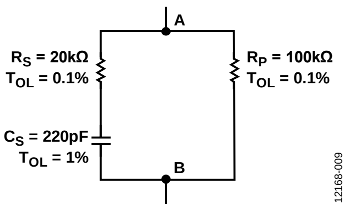


Figure 10. RC Sensor to be Measured

The total impedance of the sensor needs to be calculated to verify the system accuracy.

1. Calculate the complex sum of

   RS + *CS* = *Zs* =
   34962 ∠ −55.11

2. Calculate *Zs* || with

   Rp = *ZT* = 28337.15 ∠ −41.66

This is the total impedance of the RC sensor to be measured.

4-WIRE BIO-ISOLATED NETWORK

For this 4-wire example, select the following components:

- A lead access resistor, R_{ACCESS} = 4.99 kΩ
- An isolation capacitor, C_{ISO}, of 47 nF

If Z is close to or less then R_{ACCESS}, a potential divider effect occurs which limits the bandwidth of the ADuCM350 thus degrading accuracy (see Figure 11).

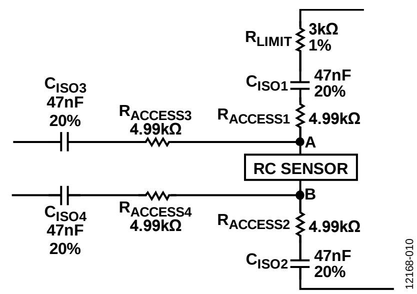


Figure 11. 4-Wire, Bio-Isolated Measurement Network

AFE OPTIMIZATION

Optimizing the ADuCM350 consists of the following steps:

1. Calculate the R_{LIMIT} resistor.
2. Calculate R_{TIA}.
3. Calculate R_G of the AD8226.
4. Calculate RCAL.

CALCULATE THE R_{LIMIT} RESISTOR

When calculating the R_{LIMIT} resistor, note that

Maximum output voltage from ADuCM350 = 600 mV peak

Maximum allowed ac current at 30 kHz is

300 µA rms (targeting IEC-60601) = 424 µA peak

Being conservative, set the maximum allowable ac current to 200 µA peak (<50%).

R_{LIMIT} ~= 600 mV peak/200 µA peak = 3 kΩ.

This calculation ignores C_{ISO} due to its small size.

CALCULATE R_{TIA}

R_{TIA} is the feedback resistor on the TIA to convert the current to a voltage.

Minimum impedance/maximum current seen by the TIA is

$$Z_{PNMIN} = \sqrt{(Real)^2 + (Sumofimaginary)^2}$$

$$\sqrt{\left(R_{LIMIT} + R_{ACCESS1_{MIN}} + Z_{UNKNOWN_{MIN}} + R_{ACCESS2_{MIN}}\right)^2 + \left(XC_{ISO1_{MIN}} + XC_{ISO2_{MIN}}\right)^2}$$

Assume 20 kΩ is the minimum impedance of $Z_{UNKNOWN}$.

$R_{ACCESS1} = R_{ACCESS2}$ = 4.99 kΩ

R_{LIMIT} = 3 kΩ

$XC_{ISO1} = XC_{ISO2}$ = 289.37 Ω

Z_{PNMIN} = 32.985 kΩ

Note the following:

- Maximum voltage swing is 600 mV peak.
- Highest signal current into TIA = 600 mV peak/32.98 kΩ = 18.19 µA peak.
- Peak voltage at output of TIA (maximum allowed by the ADuCM350) = 750 mV peak.
- R_{TIA} resistor to give peak 750 mV voltage for peak signal current is as follows:
  R_{TIA} = 750 mV/18.19 µA
  R_{TIA} = 41.2 kΩ

To prevent overranging of the ADC, put in a safety factor of 1.2, that is, the minimum impedance is 1.2 times less than the specified minimum impedance of

32.985 kΩ = 27 k Ω
R_{TIA} *with safety factor included* = 41.2 kΩ/1.2
R_{TIA} = 34.3 kΩ

Note that 33 kΩ is used for this example.

CALCULATE R_G OF THE AD8226

The maximum impedance of sensor

$$Z_{UNKNOWN_{MAX}} = 28.337\ \text{k}\Omega$$

A safety factor is incorporated on the R_{TIA} to prevent the ADC from overranging. The same needs to be done here thus the maximum peak current is divided across differential inputs of AD8226 by a factor of 1.2.

Peak current seen at V_{IN}*(AD8226)* =

(18.19 µA peak)/1.2 = 15.16 µA peak

V_{IN}*(AD8226)* =
15.16 µA peak × 28.337 kΩ = 439.6 mV peak

AD8226 G = 750 mV peak/(439.6 mV peak) = 1.706

If a further safety factor of 1.1 is used on the peak-to-peak of the voltage (this may be unnecessary for the application), then

AD8226 G = 750 mV peak/(1.1 × 439.6 mV peak) = 1.55

AD8226 G = 1 + (49.4 kΩ/*RG*) = 1.55

RG = (49.4K)/(1.55 − 1) = 89.8 kΩ

Select an RG of 100 kΩ since it is a standard value.

AD8226G = 1 + (49.4 kΩ/*RG*) =

1 + (49.4 kΩ/100 kΩ) = 1.494

Note that the AD8226 has bandwidth limitations. For a frequency of 50 kHz, the gain is limited to 10 (see Figure 12).

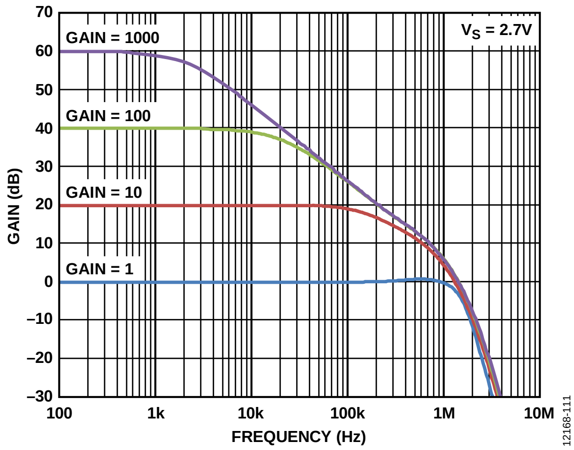


Figure 12. Gain vs. Frequency of AD8226 at 2.7 V

CALCULATE RCAL

The calibration of the auxiliary channel and TIA channel must take into account the gain through the system.

- For the voltage measurement channel, the auxiliary channel is calibrated.
- For the current measurement channel, the temperature sensor is calibrated and the results are loaded to the offset and gain registers of the TIA channel. This ensures that the difference between the voltage and current gain is exactly 1.5.

All this is done for the user in the 4-wire bio-isolated example code in the software development kit.

4-WIRE BIO-ISOLATED MEASUREMENTS

HARDWARE SETUP FOR 4-WIRE BIO-CONFIGURATON BOARD

When setting up the EVAL-ADuCM350EBZ motherboard

- For the voltage measurement, insert LK1 (Auxiliary Channel A).
- Open LK6.

For the ADuCM350 4-wire bio-configuration board

- Insert LK7, LK8, LK9, and LK10.
- To measure the network shown in Figure 10 and Figure 11, insert LK16, LK17, and LK21. The result should appear as shown in Figure 13.

By default, the 4-wire configuration seen in Figure 10 and Figure 11 is setup on the 4-wire bio-configuration board.

SOFTWARE SETUP FOR 4-WIRE BIO-CONFIGURATION BOARD

Firmware Example

Code available in the ADuCM350 software development kit is designed to be used with the 4-wire bio-configuration board to validate the solution discussed in this application note.

The Readme.txt in the example folder provides more details on the measurement.

1. After downloading the software development kit, go to **C:\Analog Devices\ADuCM350BBCZ\EVAL-ADUCM350EBZ\examples**.
2. Click the **BioImpedanceMeasurement_4Wire** folder.
3. Click the **.eww** file in IAR.
4. During the download and debug stage, open the **Terminal I/O** window to read the returned results.

Measurement Results

Impedance Magnitude

Measured result = 28405 Ω

Theoretical value measured Z_T = 28337 Ω

However, the Cs of 220 pF used in the calculation had a tolerance of 1%.

Upon analysis, the capacitor measured closer to 221 pF.

In theory, a Cs of 221 pF would give a ZT of 28416 Ω vs. the measured result of 28405 Ω.

For more details, refer to the Sensor Configuration section.

Impedance Phase

The current 4-wire-bio-isolated configuration is not capable of measuring accurate phase measurements.

If an absolute phase measurement is required, use a single chip ADuCM350 4-wire measurement configuration. Note that this configuration does not have isolation capacitors (C_{ISO}).

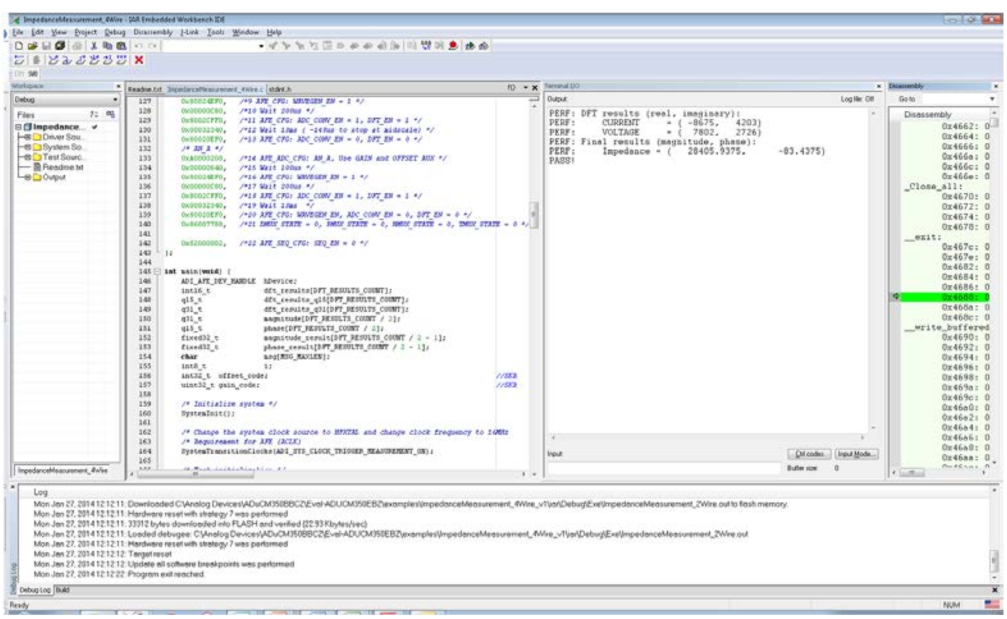


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Figure 13. 4-Wire Measurements Display on Terminal I/O

SCHEMATICS FOR THE 4-WIRE BIO-CONFIGURATION BOARD

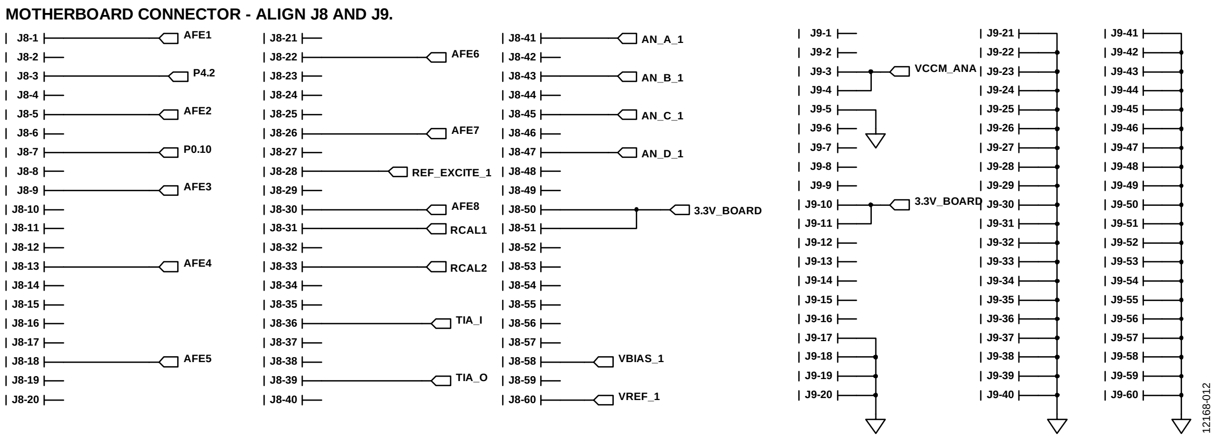

Figure 14. Motherboard Connector

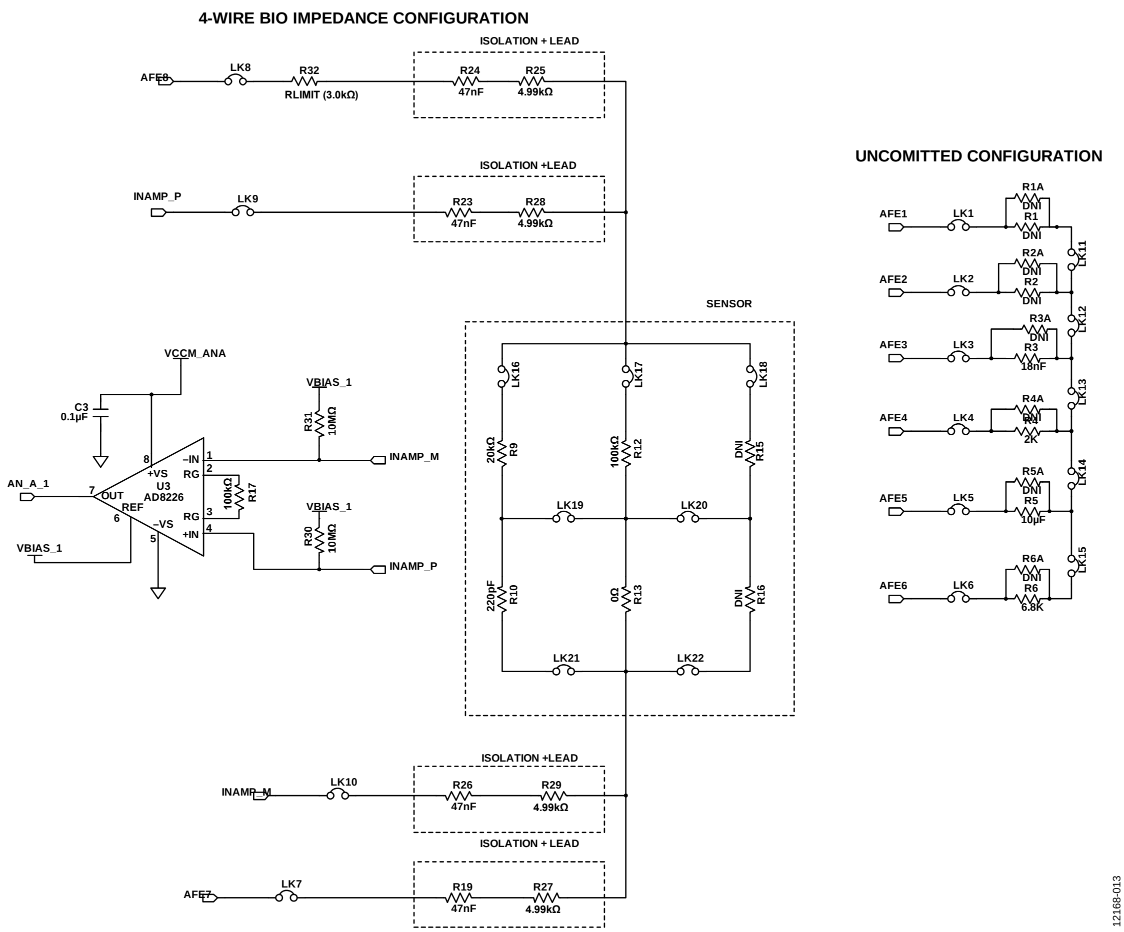

Figure 15. 4-Wire and Uncommitted Schematics

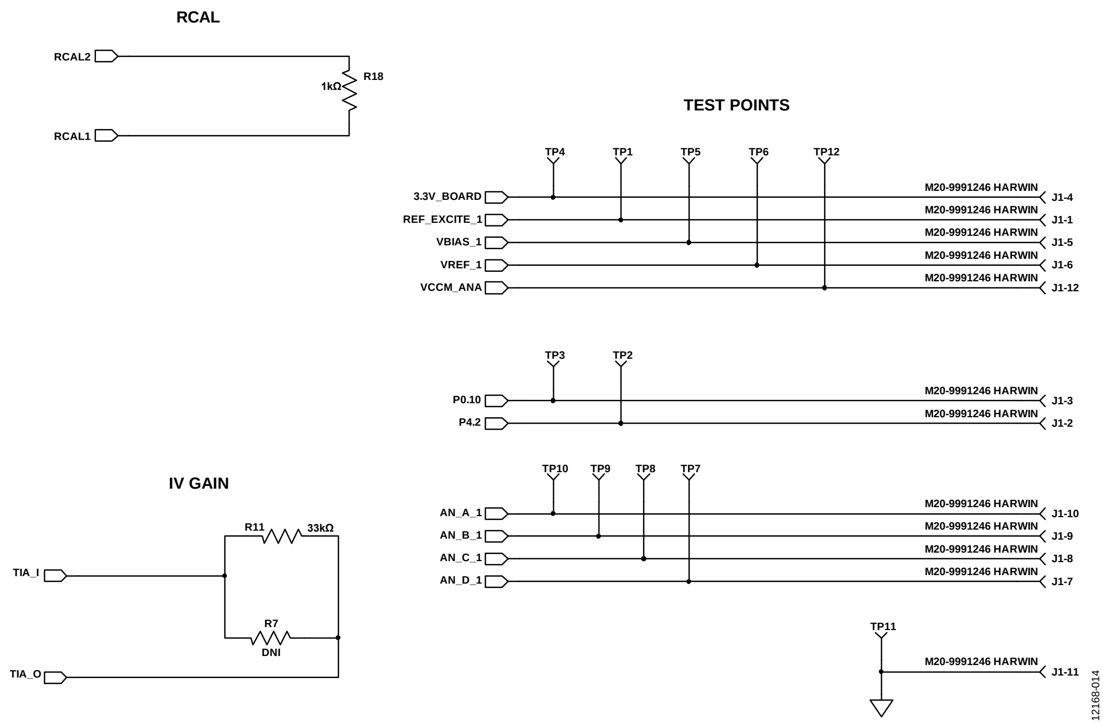

Figure 16. Miscellaneous Schematics

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